Evolution of Electron Beam (E-Beam) Treatment for Water

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Workshop on Application of Electron Beam (EB) Technology on WW & Biosolids Treatment
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Collaborators

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Michael G. Nickelsen, Haley & Aldrich, Inc.
Kimberly Kunihiro, Orange County Utilities

What is an “E-Beam”?

Most of us (used to) have one or more in our home!

Conventional CRT computer monitors or televisions

Electron Gun ➔ Accelerator emits electrons @ 25,000 Volts

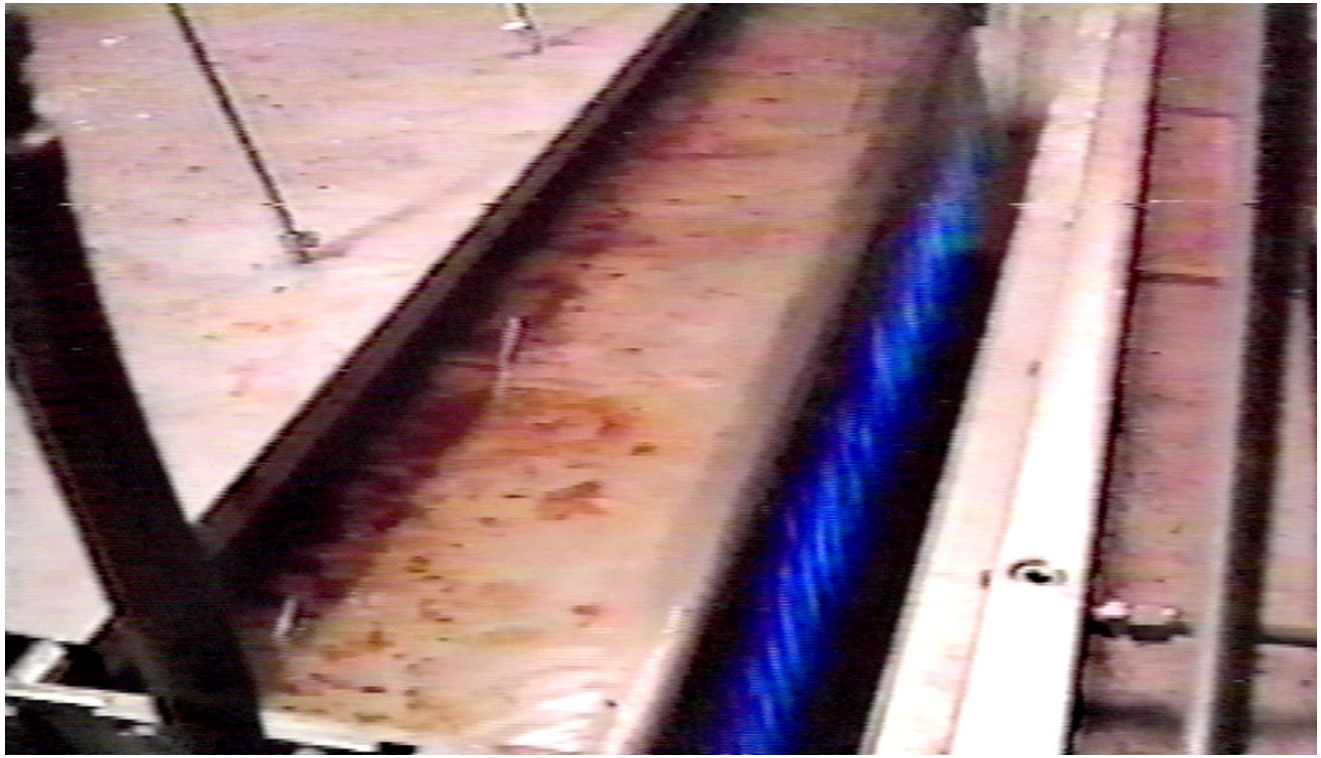
Scanned to create images

http://en.wikipedia.org/wiki/File:Egun.jpg
Thermionic electron gun assembly found on a color Samsung CRT monitor. The gun produces three high speed individual electron beams for the three primary colors (Red, Green, and Blue)

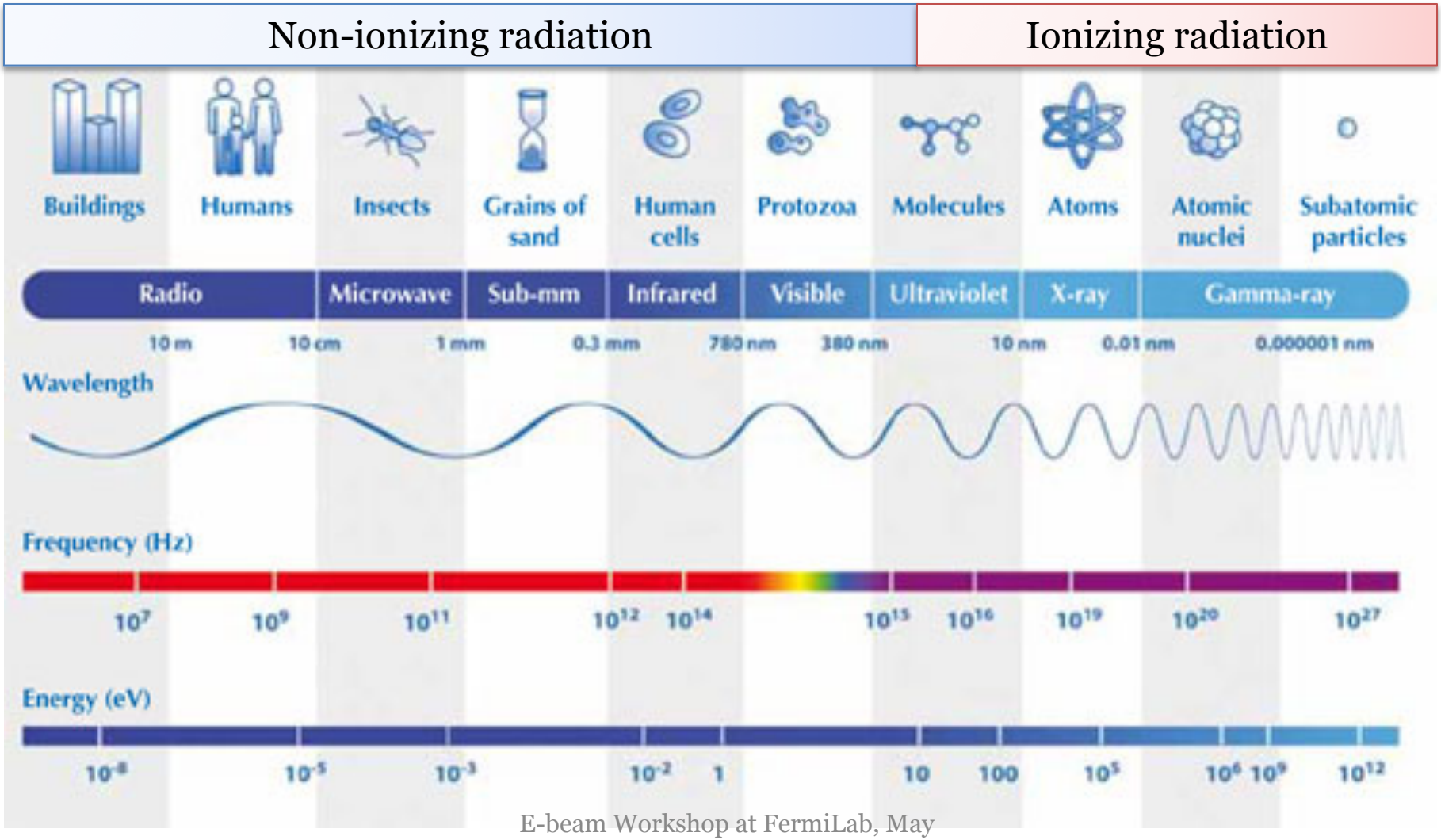
www.e-wastesolutions.net

E-Beam for Water Treatment

Accelerator → Electrons @ 500,000 to 1,500,000 volts (75 kW or more) scanned to penetrate water or vapor.



The Electromagnetic Spectrum



http://www.scienceinschool.org/2011/issue20/em (ESA/AOES Medialab)

Some Common Irradiation Uses

- Foods:
  - Insect control
  - Inhibits sprouting
  - Controls mold
  - Inactivates pathogens (e.g. *E. coli*, norovirus, *Trichina* parasite, etc.)
  - Increases shelf life
- Sterilization:
  - Medical supplies & packaging
  - Hospital waste
  - Blood and tissues for transfusions
- Materials Processing:
  - Composite materials curing
  - Crosslinking
  - Semi conductor enhancement

www.NPR.org Lui Kit Wong/MCT /Landov

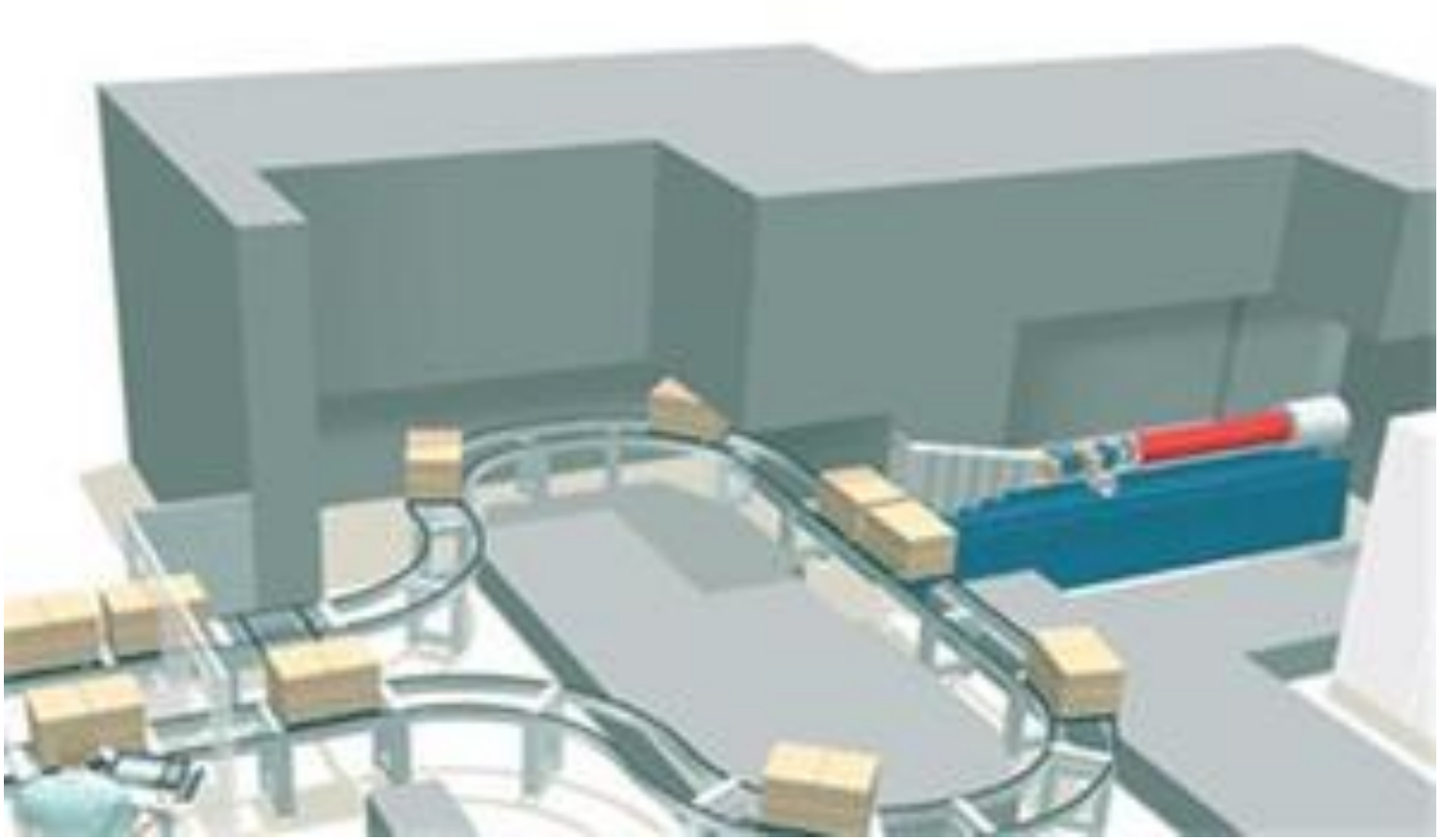
Not irradiated

Irradiated

http://www.global-peace.go.jp/en/qfile/a07.html
Photo provided by the Shihorocho Agricultural Cooperative Isotope Irradiation Center

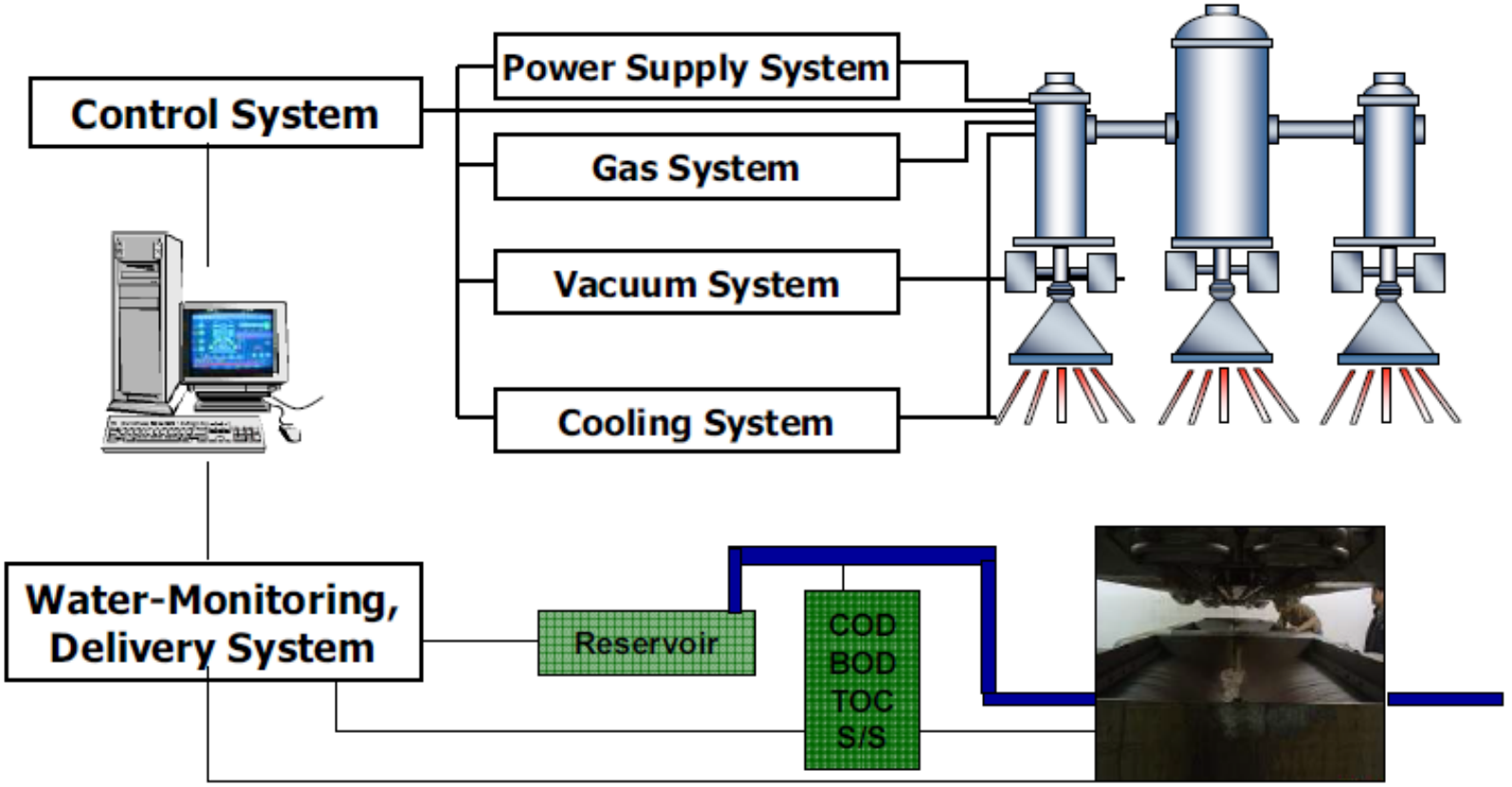
http://www.arserrc.gov/www/fsit/FoodIrradiation.htm

Industrial Applications of E-Beam Sterilization



Source: tactic-tech.com via: http://www.homelandsecuritynewswire.com/dr20120408-ebeam-technology-to-keep-food-supply-safe

Configuration of e-beam Wastewater Treatment



Virginia Key WWTP (Miami, FL) Large Scale Studies

Treated Water: 100 – 150 gallons per min.

Virginia Key E-Beam Demonstration Scale Pilot Plant

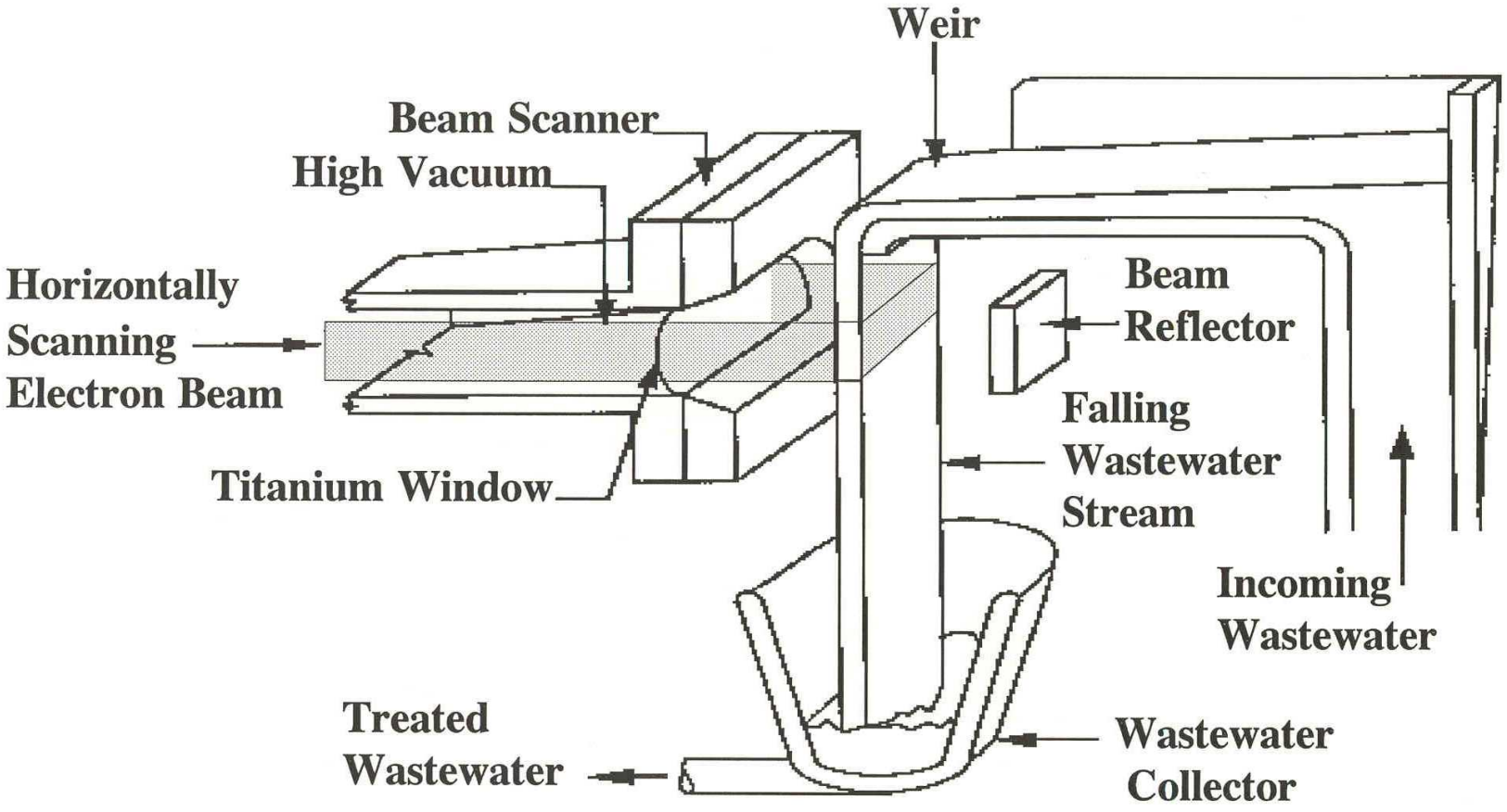
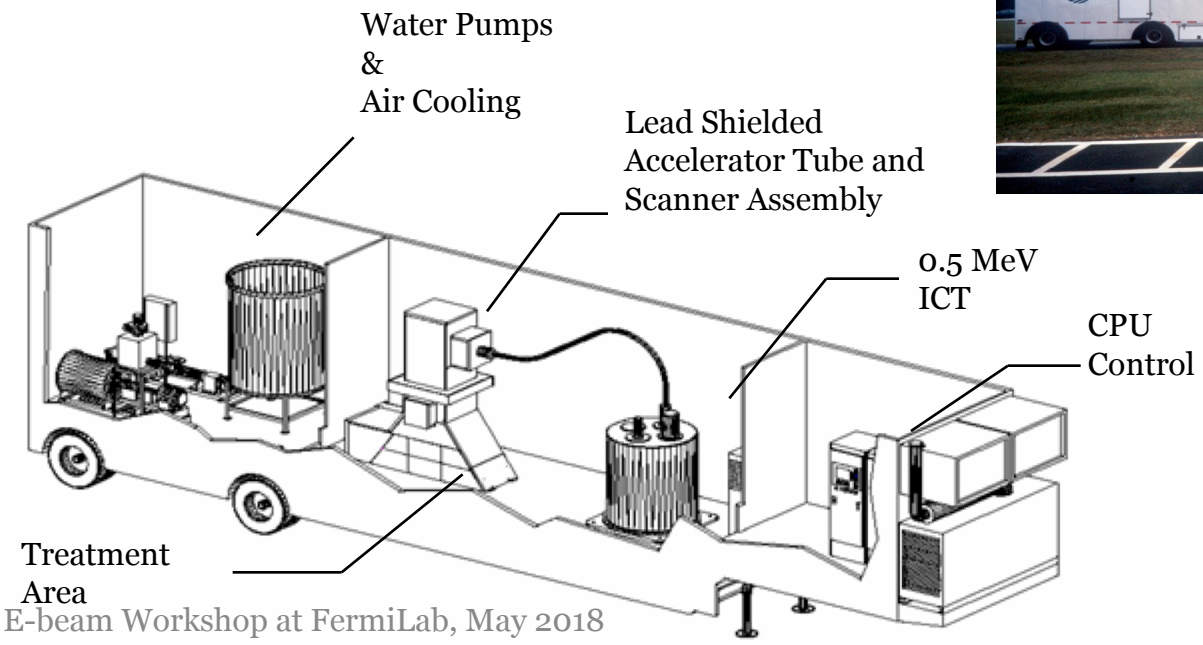


Diagram of the Electron Beam Scanner and Weir Assembly

Electron Beam Research Facility at the Austrian Research Center, Seibersdorf, Austria

- Bench scale flow through system
- Flowing aqueous stream (3 m^3/hr)
- 500 kV, 25 mA, scan width 1.2 m (High Voltage Engineering, USA)
- 400 up to 2000 Gy/s
- Enabled *Cryptosporidium* inactivation studies
- City of Vienna, Austria unchlorinated tap water

Mobile E-Beam System: High Voltage Environmental Applications, Inc.



Recycled water treated for aquifer storage & Recovery must meet "Full Treatment" defined under Florida Administrative Code 62-610

Orange County E-Beam Pilot Testing

- **Unchlorinated Reclaimed Water (Site 1)**
- **UF Permeate (Site 2)**
- **RO Permeate (Site 4)**
- **UF/RO Membrane Concentrate (Site 6)**

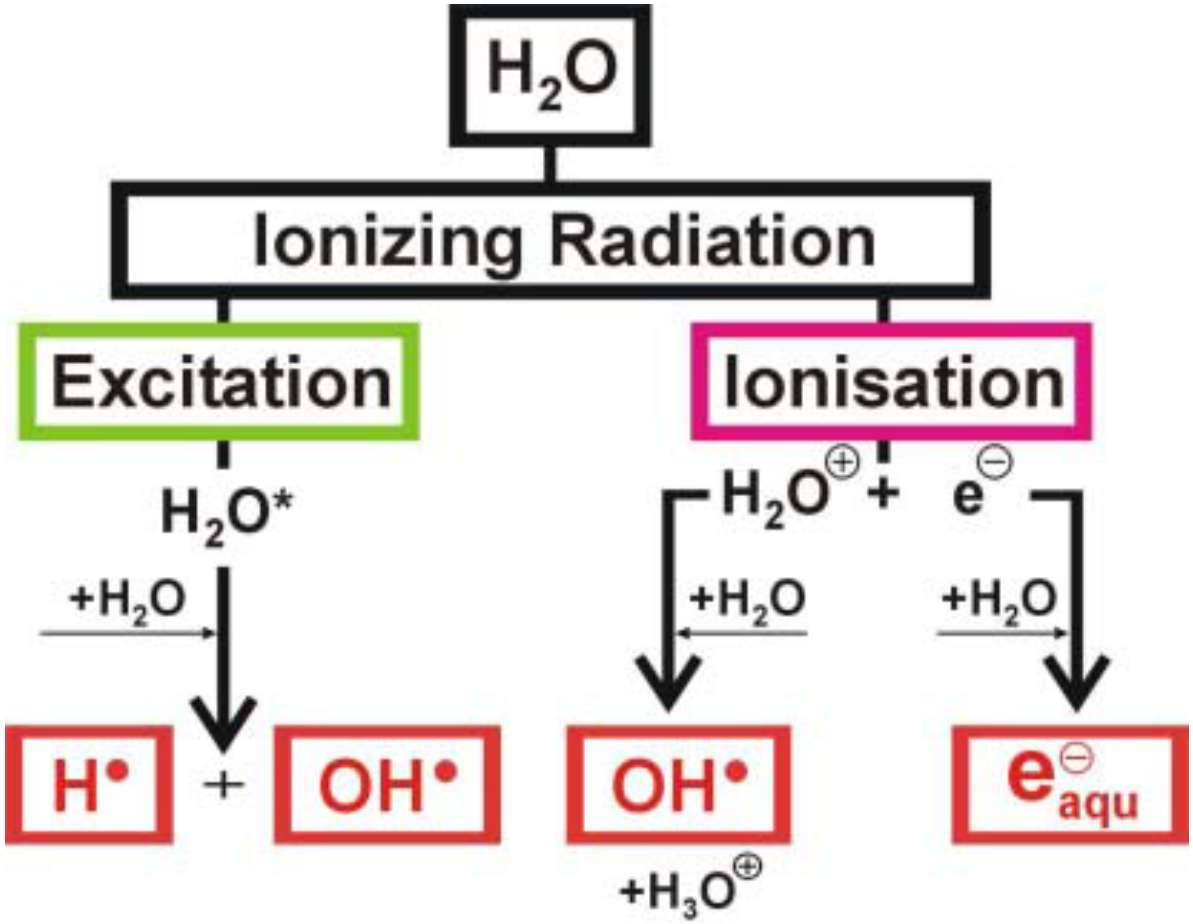
Advanced Oxidation Processes (AOPs)

- AOPs are organic contaminant destruction processes.
- Rely on *in-situ* formation of hydroxyl radicals: •OH
- Involve two stages of oxidation:
  - Formation of the strong oxidants (e.g. •OH)
  - Reaction of the oxidants with organic contaminants
- Provide a barrier to both microbial and chemical contamination
  - One process = multiple benefits & barriers
  - Effectively reduces/remOves low concentrations of organic chemicals

Some Advanced Oxidation Processes

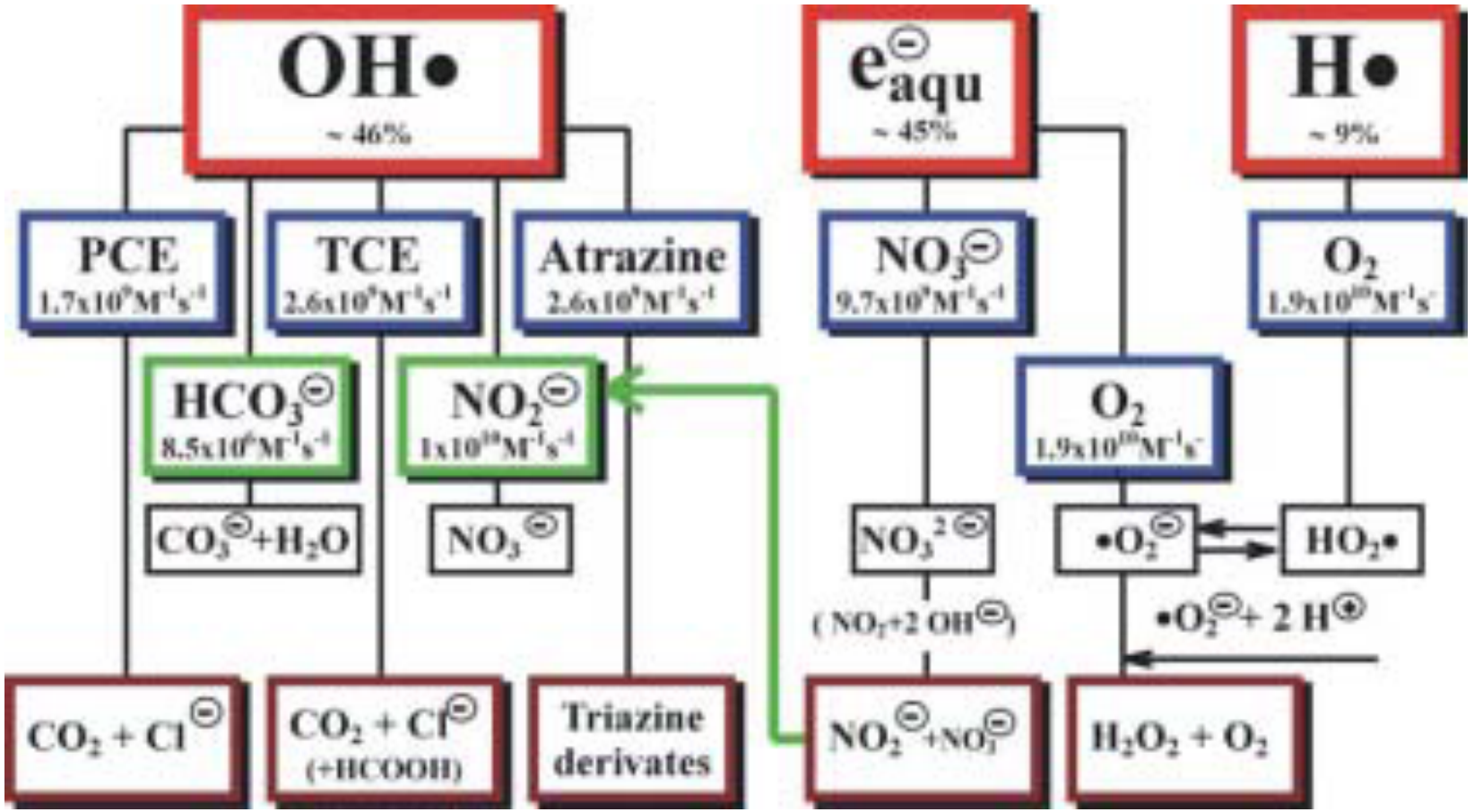
AOP	***In-situ* generated radical species**
Electron Beam	•OH (oxidizer) •H (both oxidizer & reducer) e^-_{aq} (reducer)
Ozone/H2O2	•OH
TiO2/UV light	e^-_{aq} H^+
Fenton's chemistry (Fe(II)/H2O2)	•OH
Sonolysis	•OH •H
UV/H2O2	•OH

Water Radiolysis: Formation of Free Radical Species in Water by Means of Ionizing Radiation



Gehringer, P. 2003 IAEA-TECDOC-1407.

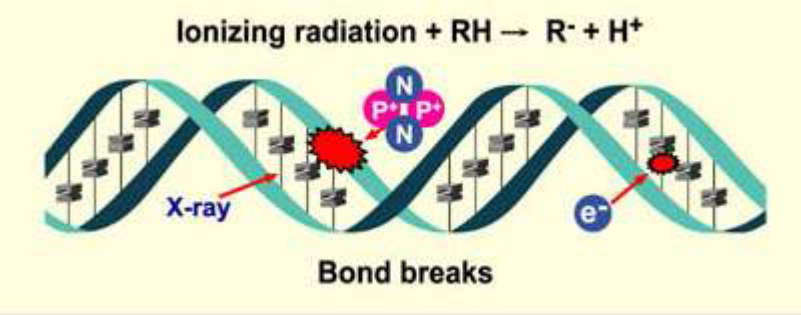
Simplified Model of the Competition for the Free Radical Species in a Natural Groundwater

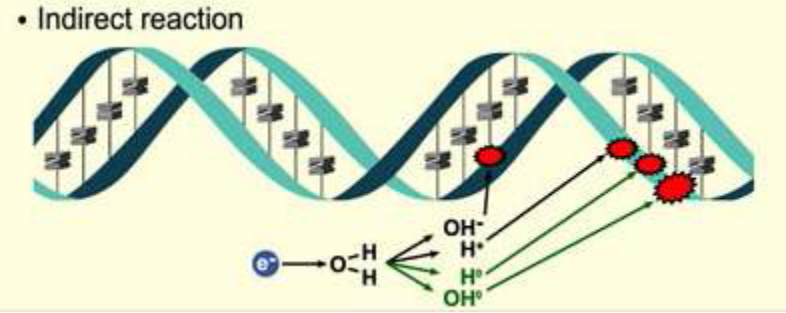


Gehringer, P. 2003 IAEA-TECDOC-1407.

E-Beam Disinfection Mechanism

- Direct effects are extremely rapid (10^{-16} seconds)
- Induced through energy deposition at sensitive target sites, typically vital sub-cellular components:
  - Enzymes
  - Nucleic acids
  - Genetic material

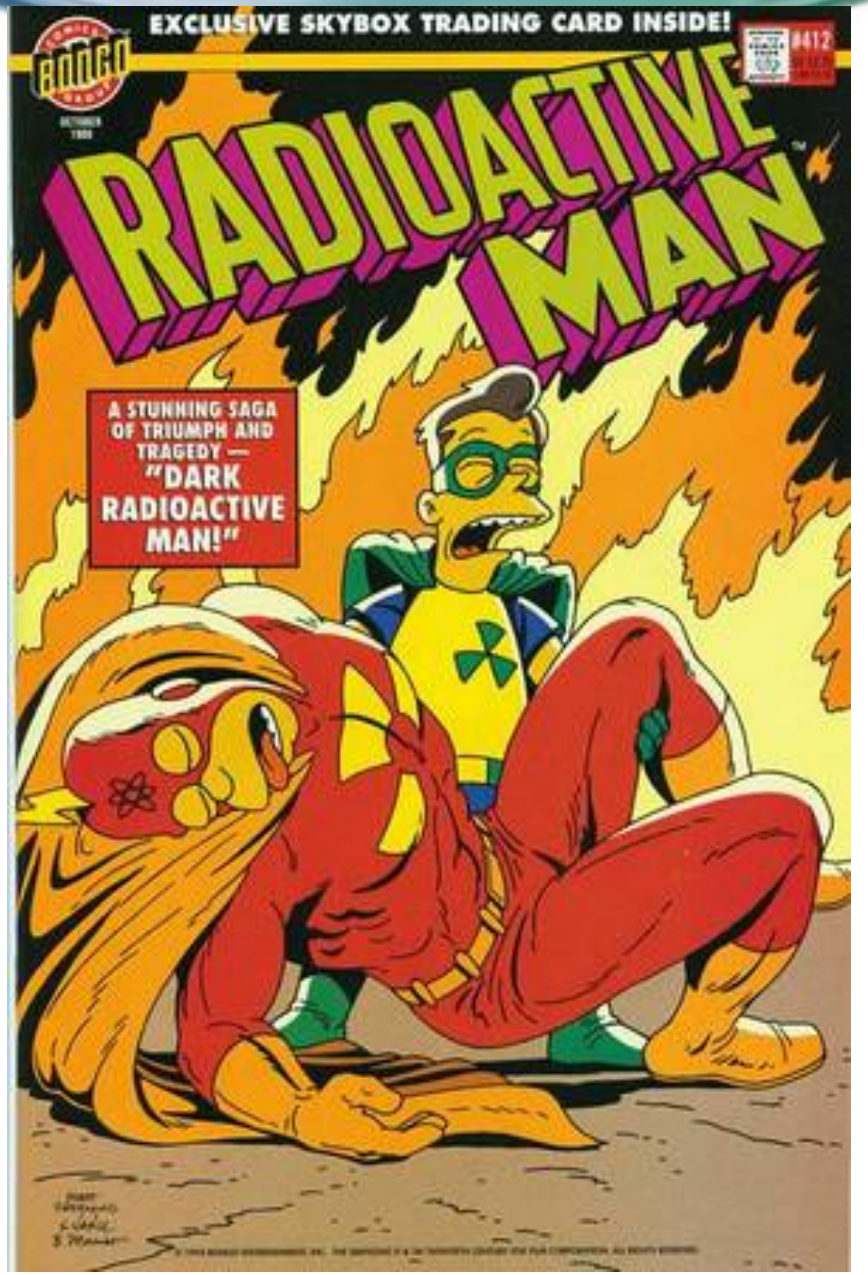




International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators, Vienna, Austria 2009. Eb-Tech, Daejeon 305-500, Korea

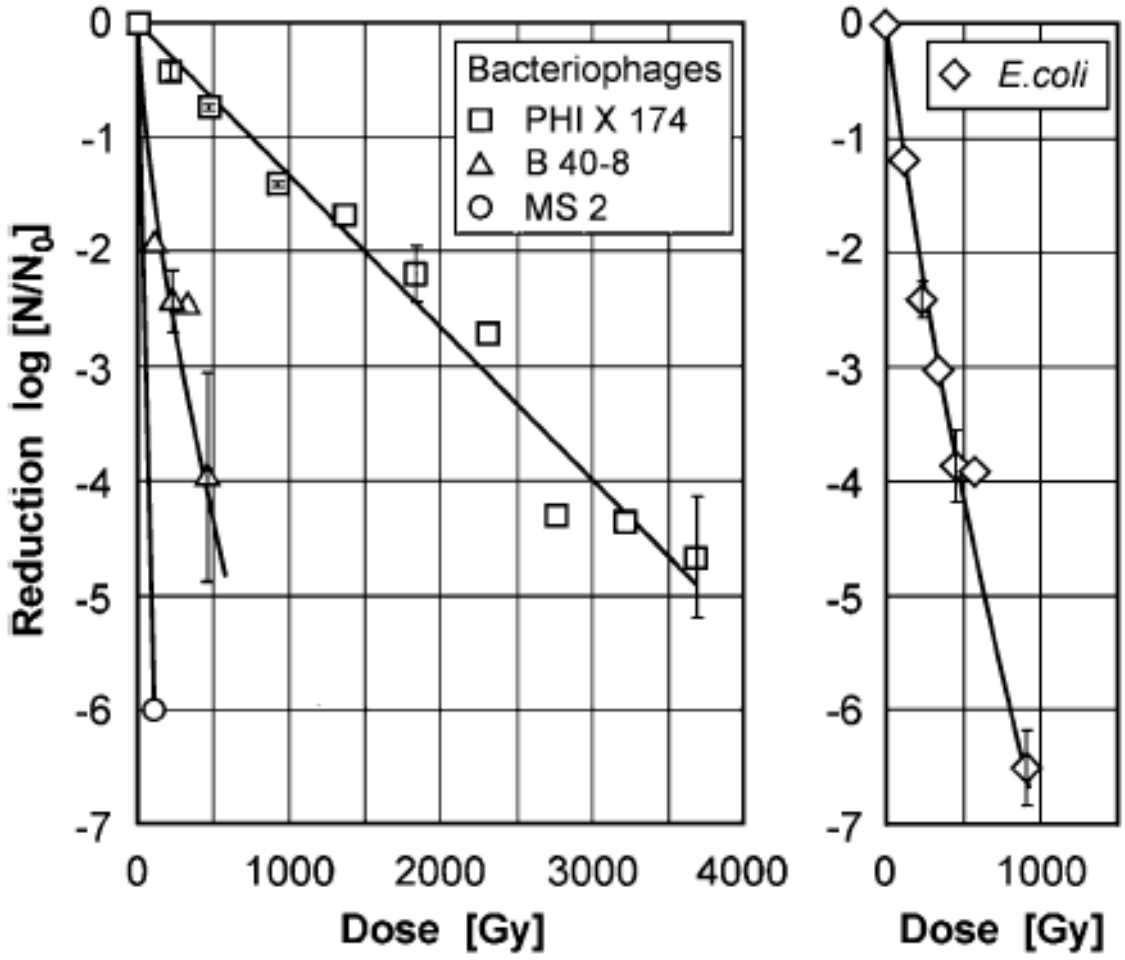
Irradiated foods, materials, water, etc., do not become radioactive.

- Particles that transmit radiation are not radioactive.
- Irradiated water creates transient radicals
  - Hydroxyl radical ($\bullet OH^-$)
  - Hydrogen atom ($\bullet H^+$)
  - Solvated electrons (e^-_{aq})
- Free radicals damage DNA and intercellular structures within living cells.



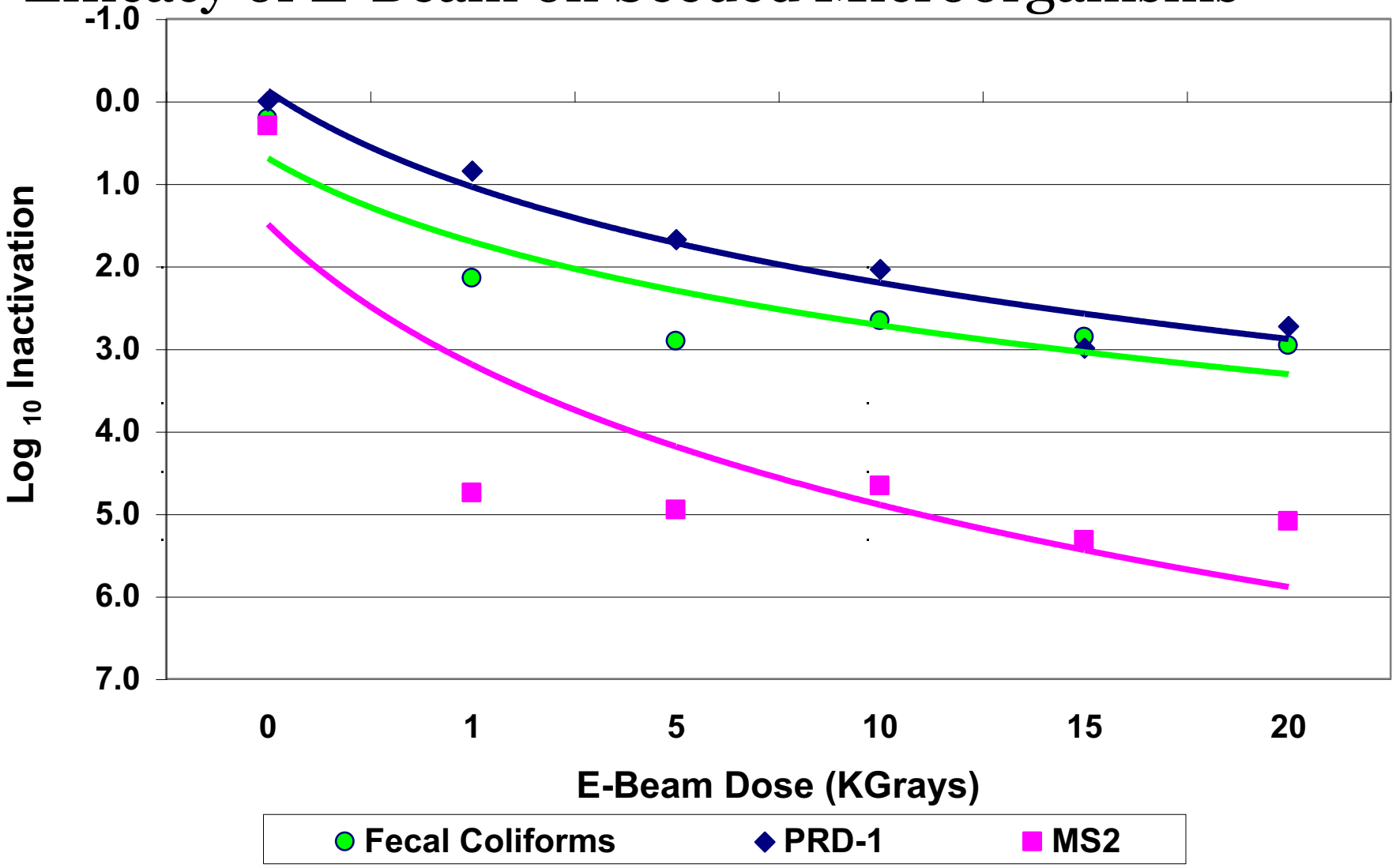
http://www.npr.org/blogs/thesalt/2012/01/12/145107755/why-x-rayed-food-isnt-radioactive-and-other-puzzles

Bacteriophage & *E. coli* Inactivation in Tap Water

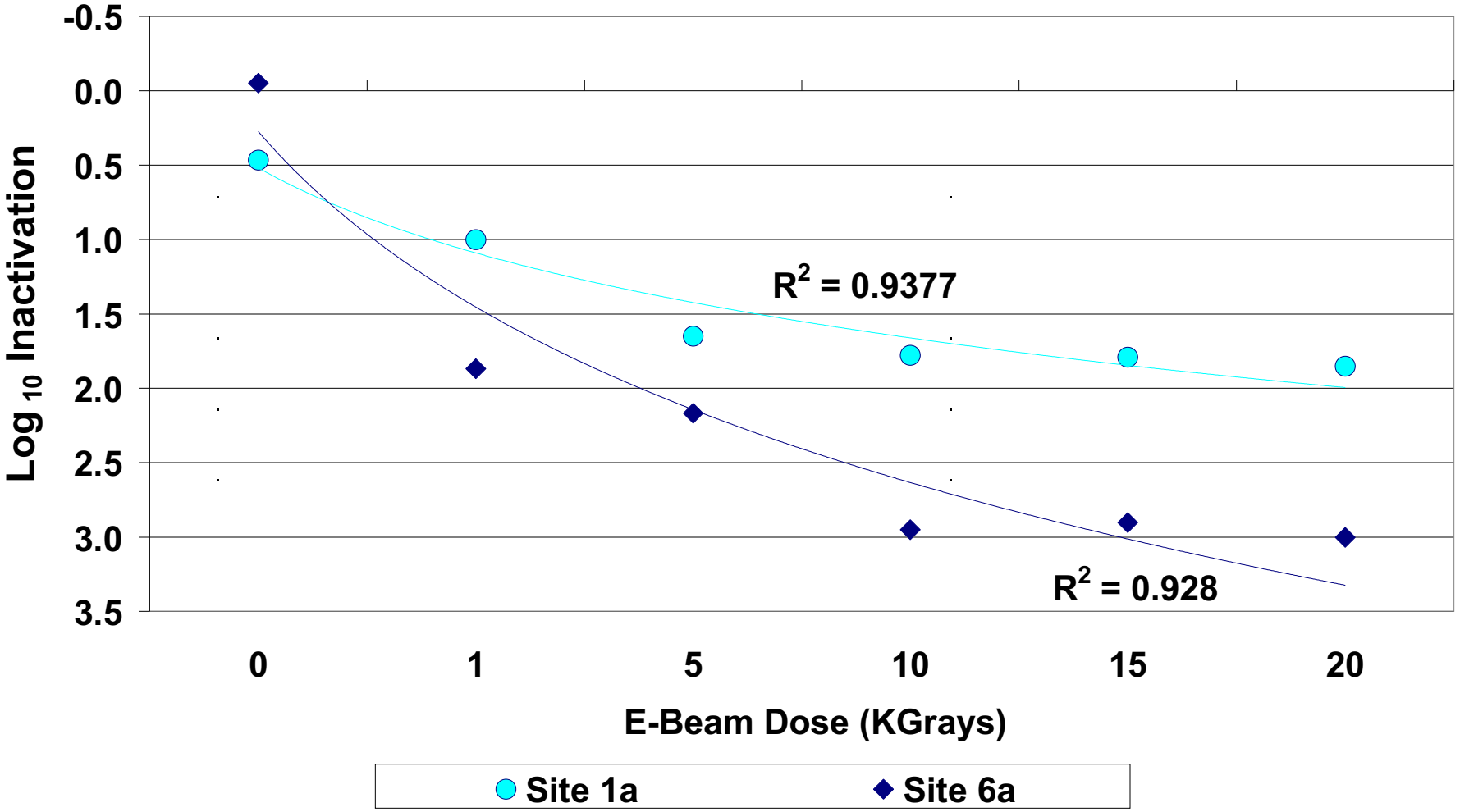


Gerhinger et al., 2003. Bacteriophages as viral indicators for radiation processing of water: A chemical approach.

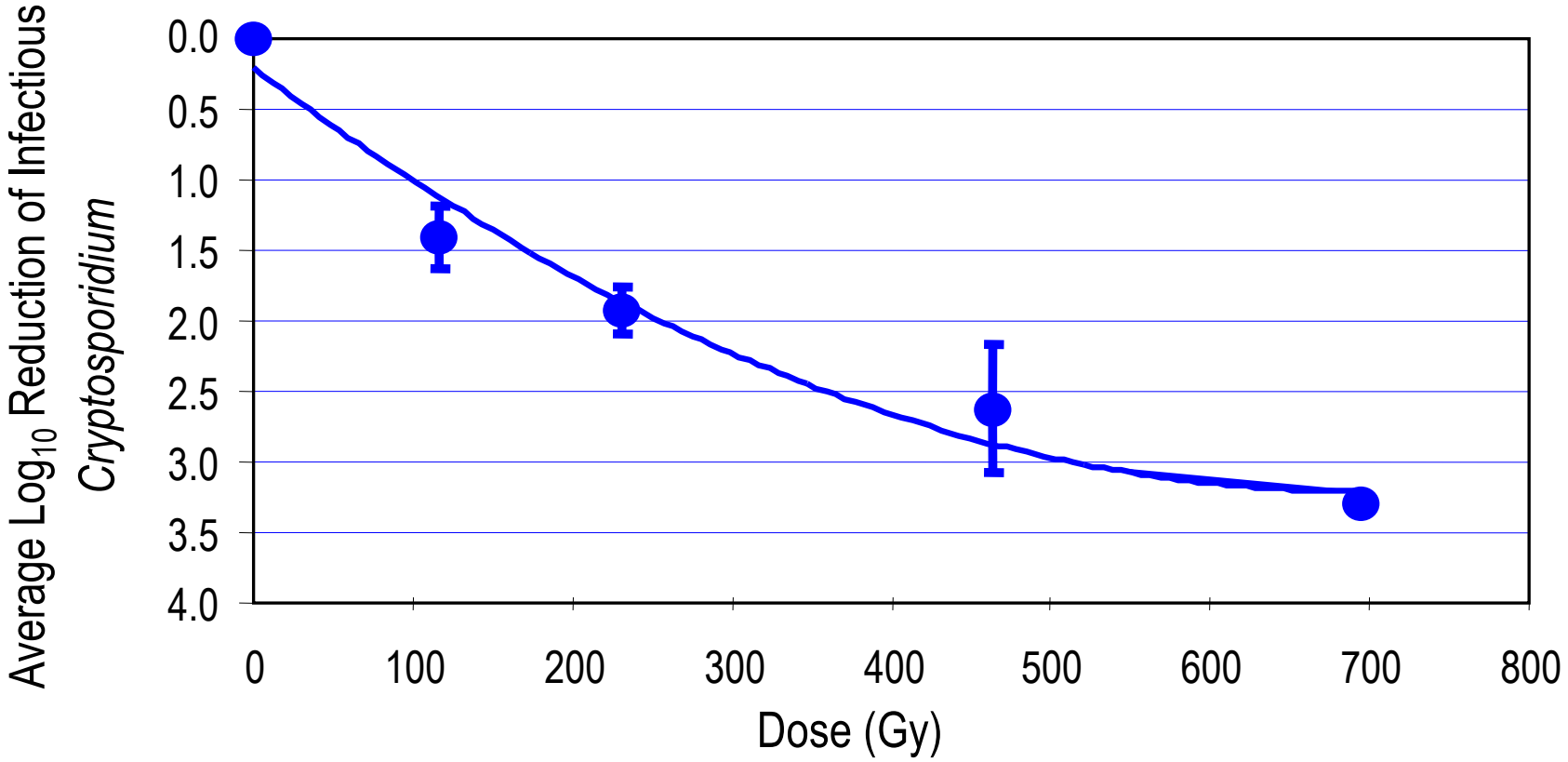
Efficacy of E-Beam on Seeded Microorganisms



Efficacy of E-Beam on HPC



Electron Beam Inactivation of *Cryptosporidium* *(Potable Water)*



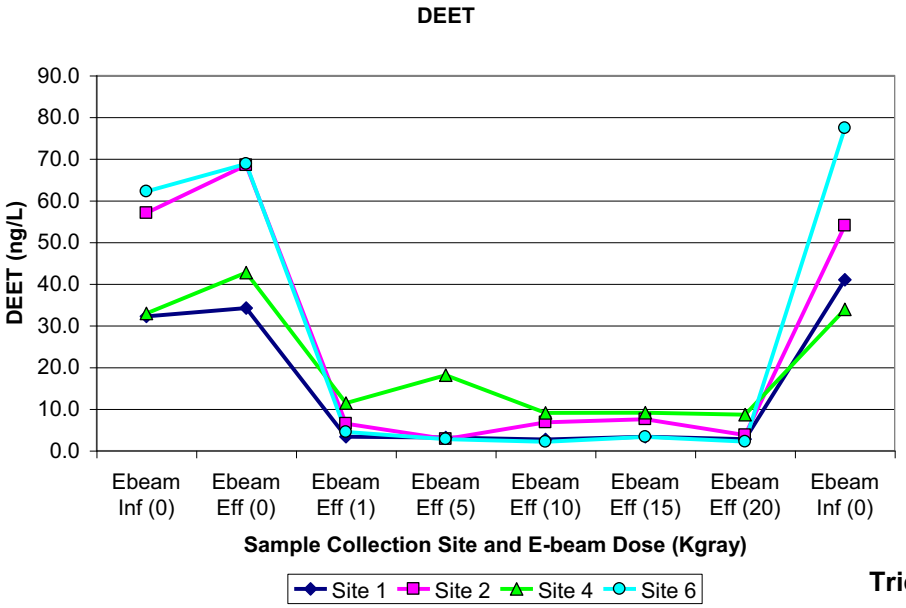
0 $0.01 → → → $0.12

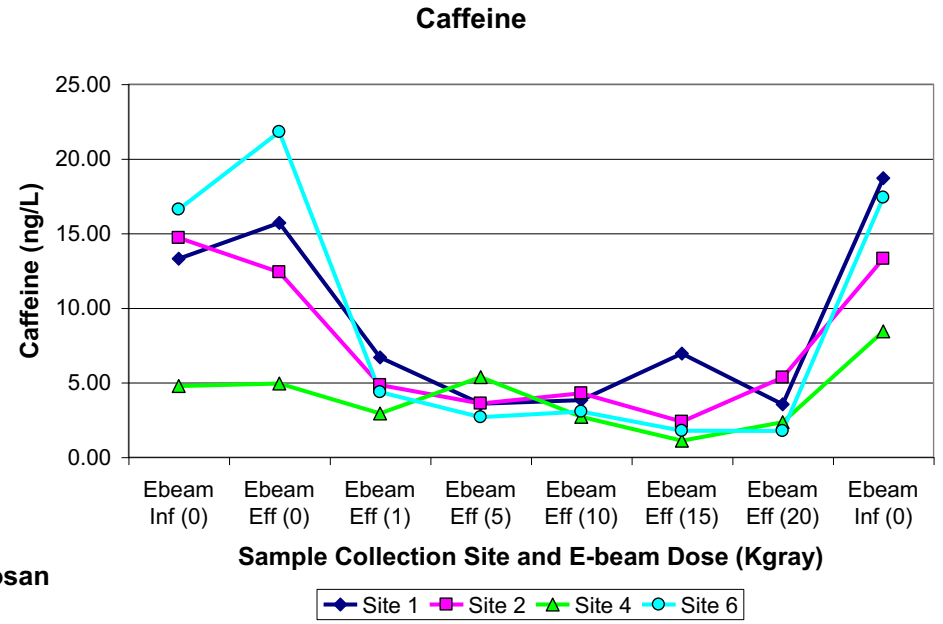
$/1000 gal

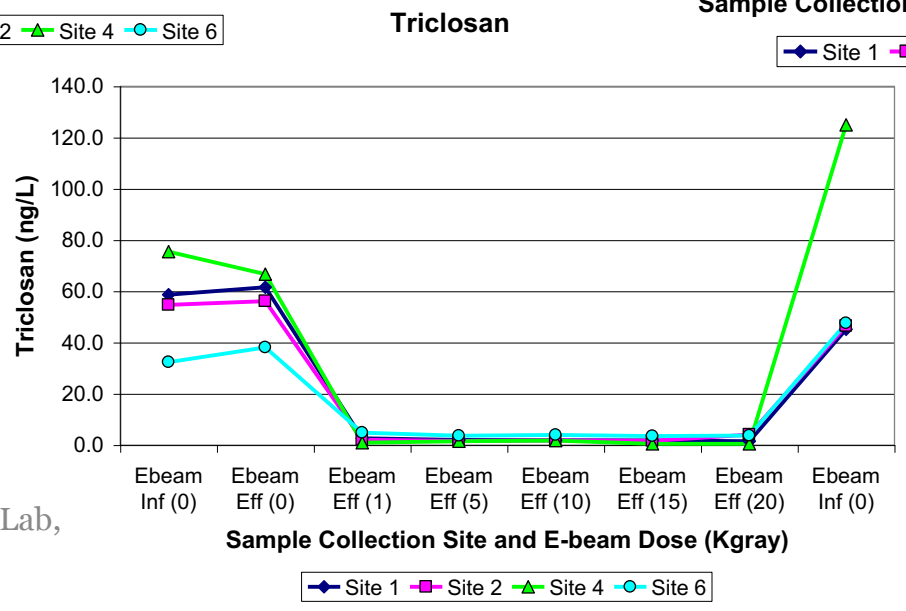
Efficacy of E-beam on Selected DBPs for each Dose on Unchlorinated Reclaimed Water (Site 1)

Compound	Percent Removal				
Ebeam Dose (Kgray)	**1**	**5**	**10**	**15**	**20**
Dichloroacetic acid	0.00	52.94	77.94	80.44	85.29
Total Haloacetic acids	4.04	62.32	84.85	86.57	89.90
Trichloroacetic acid	12.90	82.90	>93.87	>93.87	>93.87
Bromodichloromethane	16.67	>94.44	>94.44	>94.44	>94.44
Chloroform	45.15	87.97	>99.05	>99.05	>99.05
Total Trihalomethanes	52.38	89.56	>99.27	>99.27	>99.27
Removal Range	**0 - 52%**	**>53%**	**>78%**	**>80%**	**>85%**

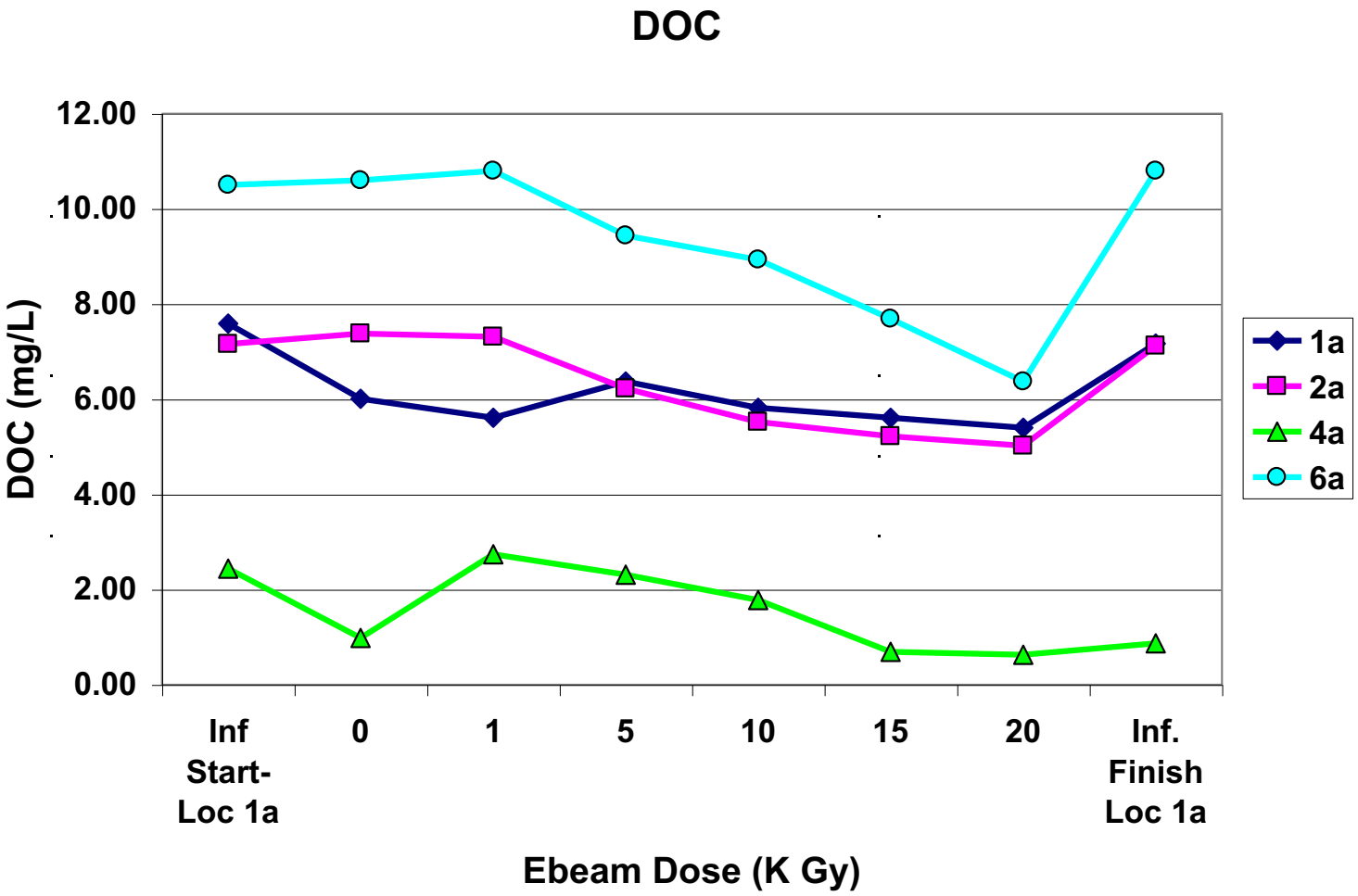
Effects of E-beam Treatment on Select Organic Compounds



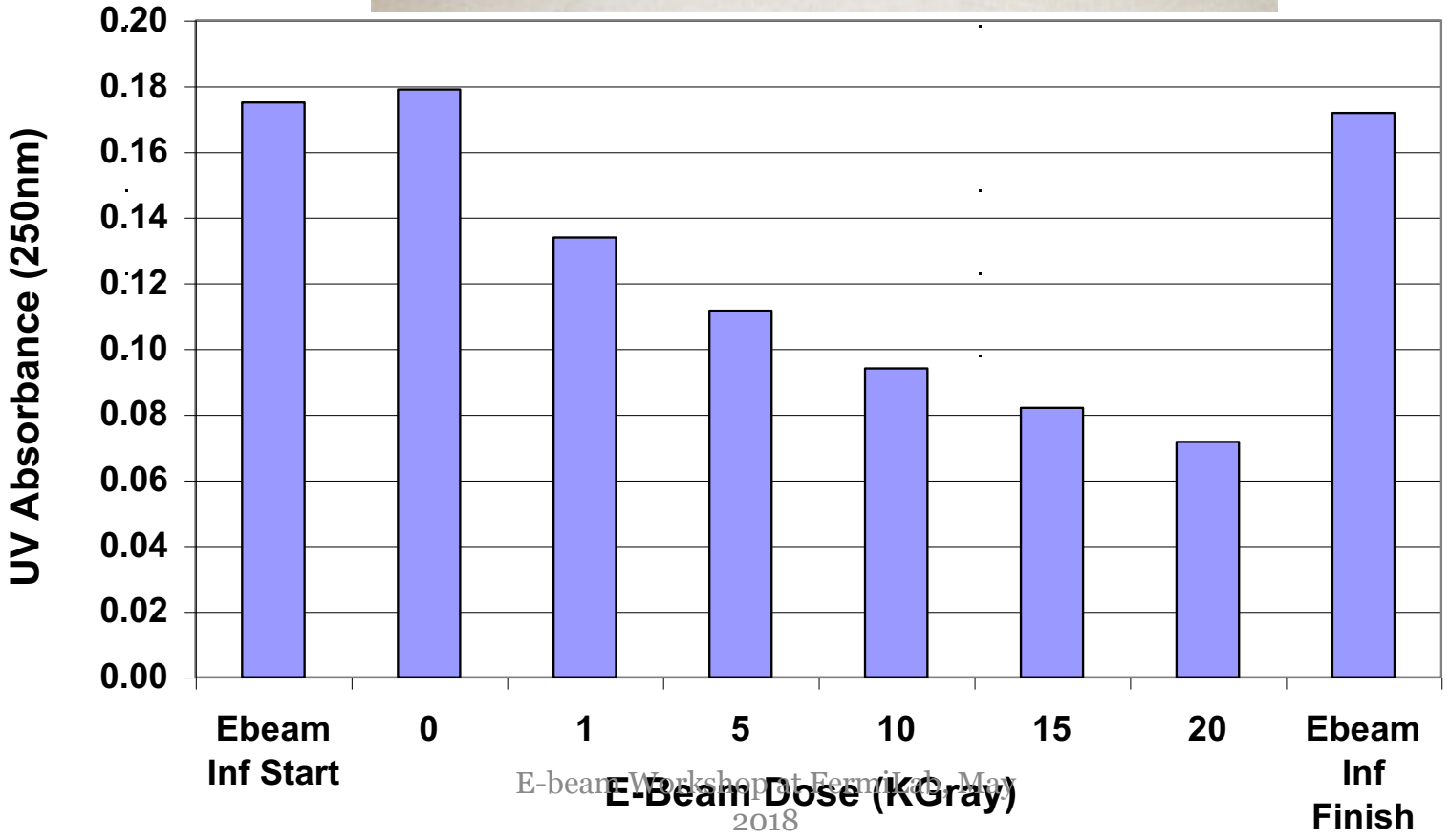




Efficacy of E-Beam on DOC

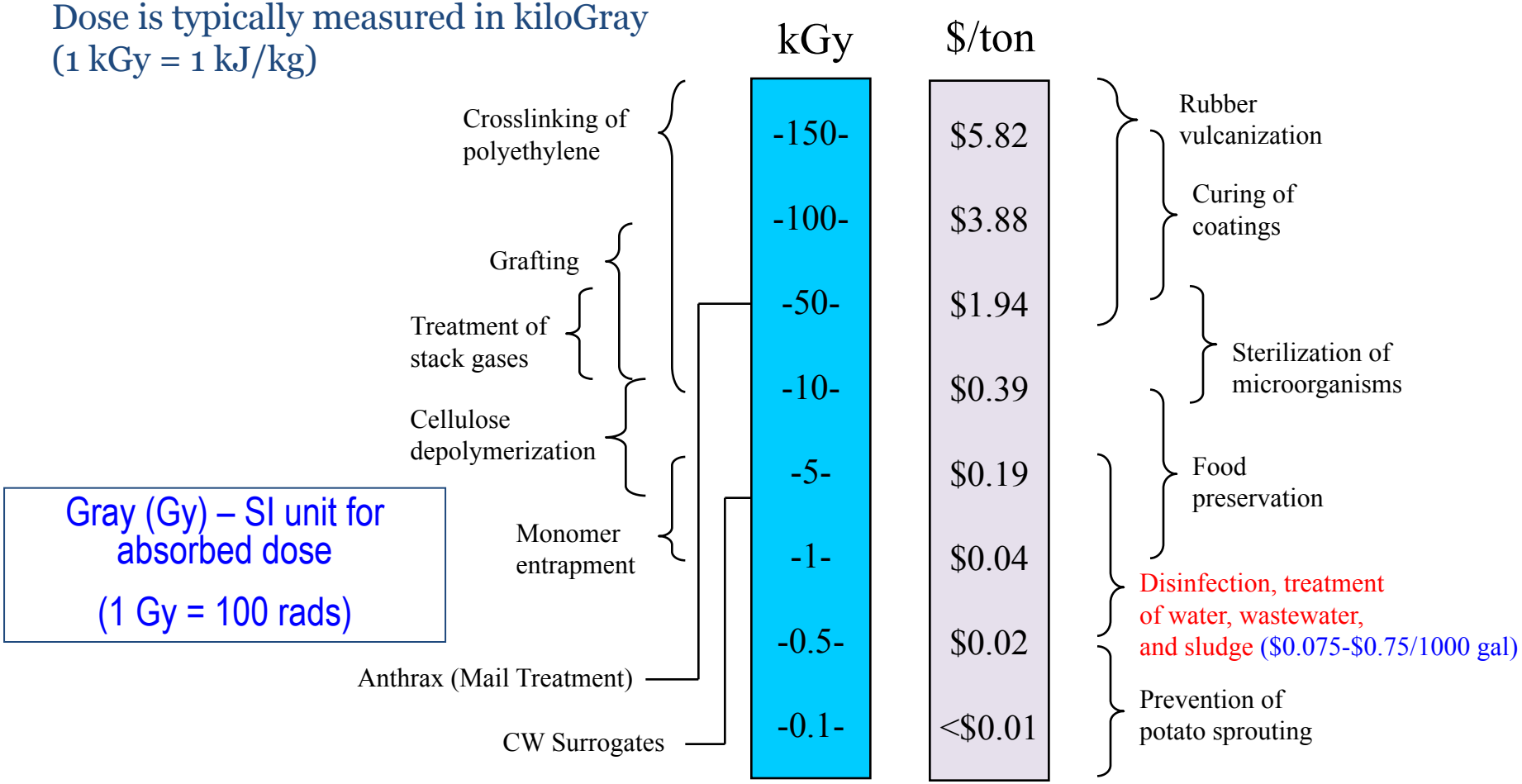


Efficacy of E-Beam on Color of Unchlorinated Reclaimed Water (250nm UV)



Dose Ranges & Cost for Various Applications

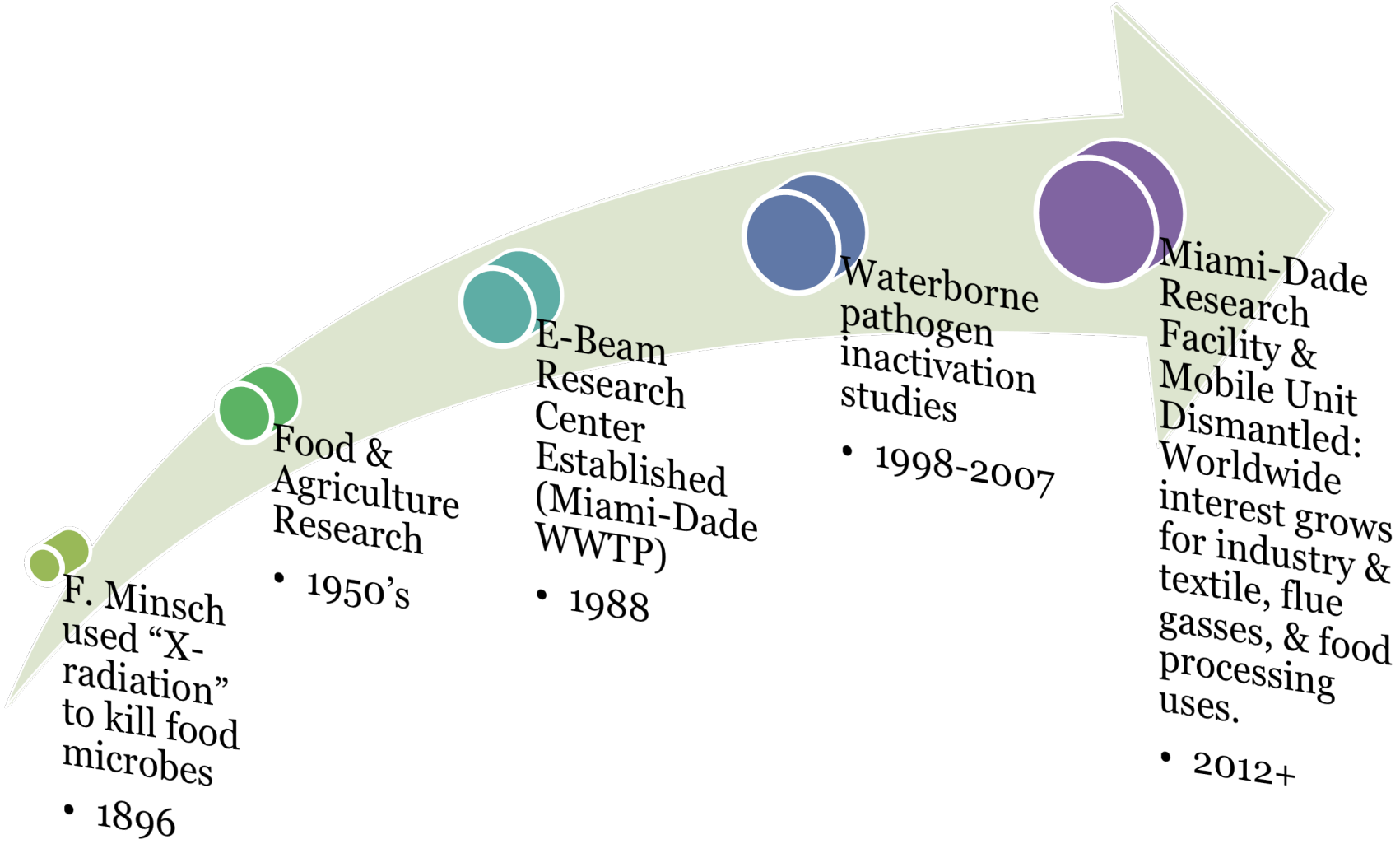
Ionizing effects are stated in terms of the absorbed dose
Dose= energy absorbed per unit mass
Dose is typically measured in kiloGray
(1 kGy = 1 kJ/kg)



Gray (Gy) – SI unit for absorbed dose

(1 Gy = 100 rads)

E-Beam for Water Treatment Timeline



E-Beam Applications for Water Treatment:

- Process is technically sound and founded on good science.
- Demonstrated capable of non-selective destruction of organic compounds:
  - Endocrine disruptors
  - Pharmaceuticals
  - Toxic Organic Chemicals
  - Pesticides
  - Disinfection By-Products (DBPs)
    - THM
    - Nitrosamines
    - Brominated compounds
- Biosolids Treatment - De-watering and Composting
  - Original Application of Miami and Deer Island (Boston)
- Disinfection achieved in complex matrices (highly turbid water, sludge, and RO membrane concentrate, textile dyes, etc., etc., etc…).

What is the most viable application of this profound and highly effective water treatment technology??

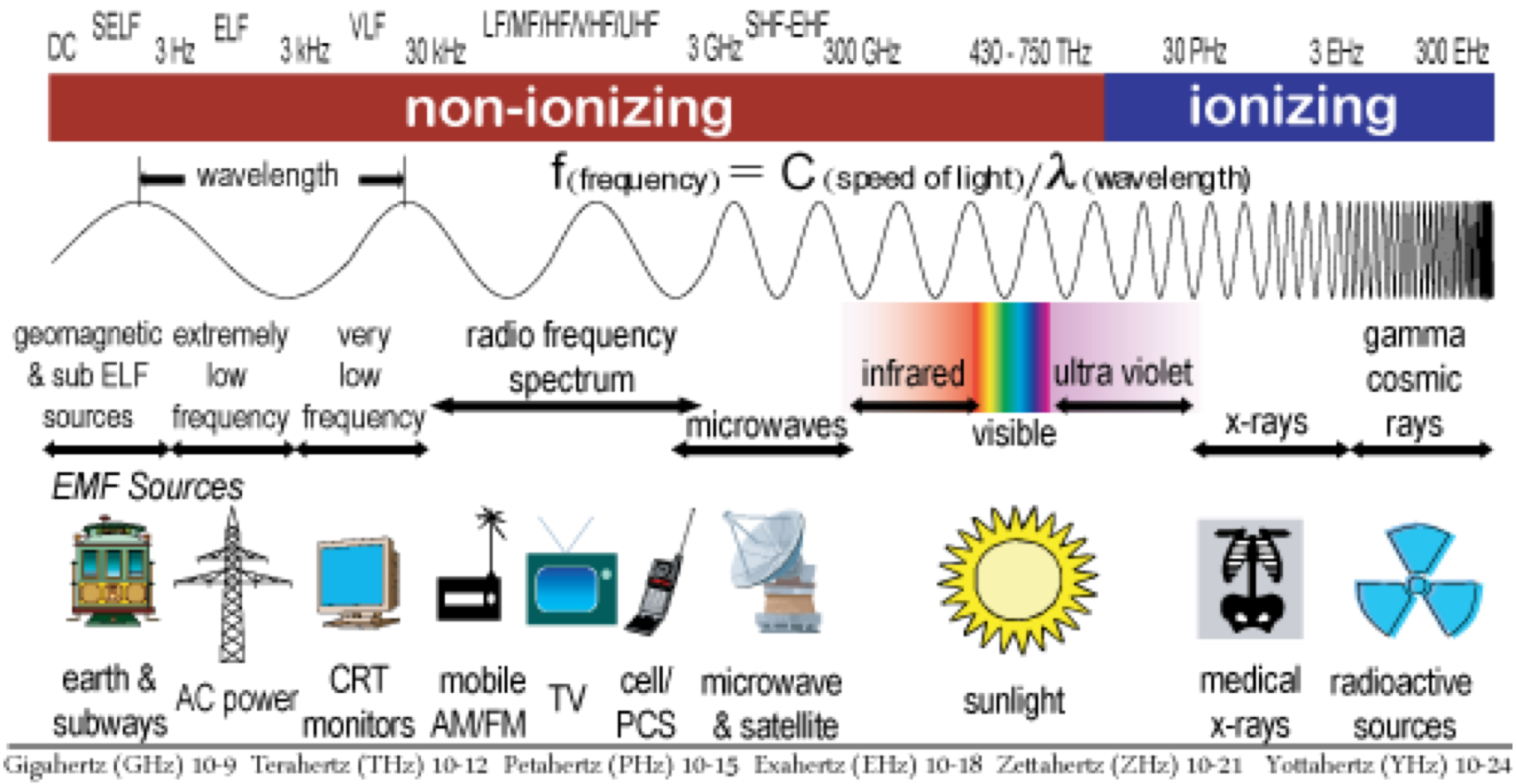
E-Beam Process

- High density electron stream injection throughout water volume resulting in formation of:
  - Electrically excited states
  - Free radicals
- Rapid Reaction Rate
  - 10^{-7} seconds after irradiation yields

$$H_2O \xrightarrow{e^-} [2.6]e^-_{aq} + [0.6]H\bullet + [2.7]\bullet OH +$$
$$[0.7]H_2O_2 + [2.6]H_3O^+ + [0.45]H_2$$

- Unique – no other AOP can generate oxidizing and reducing chemistry simultaneously
- Importance of the three free radicals (•OH, H•, and e^-_{aq})

THE ELECTROMAGNETIC SPECTRUM



The Real Difference Is The Result

- Facilitate contaminant destruction by allowing for multiple reaction pathways
  - Greater potential to mineralize
  - Less potential for reformation
- Residual disinfectant (H_2O_2)
- Energy Efficiency
- High Energy Delivery = Excellent Disinfection Capacity
  - Lethal doses
  - Instantaneous/short duration
  - USEPA approved for sludge disinfection
- Non-selective destruction of organics
- Rapid chemical reactions
  - Supports flow through applications
  - Excellent process flexibility

Why?

- pH Independent
  - Equal performance from pH 3 to 11
- Solids Independent
  - Sediments, soils, sludges
- Non Contact Apparatus
  - No fouling of lamps or membranes

Why?...continued

- Temperature Independent
  - Variations have no treatment impact
- No organic sludge
  - Organics are mineralized
  - Reduces sludge generation from secondary treatment processes (like filtration)
- No air emissions
  - Aqueous technology
    - No NO_X and SO_X

Why…continued

- Flexibility for use at either end of pipe
  - Pretreatment/post treatment
    - Organics, Microbiological
    - Extend membrane life (prevents fouling)
  - Synergy with other processes
    - Sterilize ahead of RO/filtration
    - Improve performance of Biological treatment processes
    - Treats recalcitrant compounds

El Cost n Beam Economics

- Electron beam accelerators are available from 0.5 - 10 MeV in power levels from 5 - 1000 kW
- Capital cost ($10,000 - $35,000/kW)
  - Function of system size – power requirements
    - Dose requirement
    - Linear dependence on process rate
    - Logarithmic dependence on contaminant concentration
  - Offset by low operating cost
    - $0.04/ton per kGy
    - $0.15/1000 gal per kGy
      - assumes electricity cost at $0.10 kWh and 70% E-beam utilization efficiency

Nitrite Oxidation

- Nitrite ion readily/rapidly oxidized to nitrate ion via two pathways

$$\bullet OH + \mathbf{NO_2^-} \rightarrow \bullet NO_2 + OH^-$$

$$\bullet OH + CO_3^{2-} \rightarrow CO_3\bullet^- + OH^-$$

$$\bullet OH + \bullet NO_2 \rightarrow H^+ + \mathbf{NO_3^-}$$

$$CO_3\bullet^- + \bullet NO_2 \rightarrow \mathbf{NO_3^-} + CO_2$$

NDMA Destruction

- NDMA formed from*:
  - Oxidation of UDMH $(CH_3)_2NNH_2$
  - Reaction of DMA + $HNO_2/NO_x/NH_2Cl$

- NDMA reversibly oxidized to dimethylnitramine

$$R_2NO \underset{\text{Red}}{\overset{\text{Ox}/h\nu}{\rightleftharpoons}} R_2NO_2$$

*Tuazon et al., Env. Sci. Tech. 15, 283, (1981)